

ANL-HEP-CP-00-001

DESY 00-007

Longitudinal Spin Dependence of Massive Lepton Pair Production

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Abstract

We show that massive lepton-pair production, the Drell-Yan process, should be a good source of independent constraints on the polarized gluon density, free from the experimental and theoretical complications of photon isolation that beset studies of prompt photon production. We provide predictions for the spin-averaged and spin-dependent differential cross sections as a function of transverse momentum Q_T at energies relevant for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.

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§1. Introduction

Massive lepton-pair production, $h_1 + h_2 \rightarrow \gamma^* + X; \gamma^* \rightarrow \ell\bar{\ell}$, known as the Drell-Yan process¹⁾, and prompt real photon production, $h_1 + h_2 \rightarrow \gamma + X$, are two of the most valuable probes of short-distance behavior in hadron reactions. They supply critical information on parton momentum densities and opportunities for tests of perturbative quantum chromodynamics (QCD). Spin-averaged parton momentum densities may be extracted from spin-averaged nucleon-nucleon reactions, and spin-dependent parton momentum densities from spin-dependent nucleon-nucleon reactions. An ambitious experimental program of measurements of spin-dependence in polarized proton-proton reactions will begin soon at Brookhaven's Relativistic Heavy Ion Collider (RHIC) with kinematic coverage extending well into the regions of phase space in which perturbative quantum chromodynamics should yield reliable predictions.

The Drell-Yan process has tended to be thought of primarily as a source of information on quark densities. Indeed, the mass and longitudinal momentum (or rapidity) dependences of the cross section (integrated over the transverse momentum Q_T of the pair) provide essential constraints on the *antiquark* momentum density, complementary to deep-inelastic lepton scattering from which one gains information of the sum of the quark and antiquark densities. Prompt real photon production, on the other hand, is a source of essential information on the *gluon* momentum density. At lowest order in perturbation theory, the reaction is dominated at large values of the transverse momentum p_T of the produced photon by the “Compton” subprocess, $q + g \rightarrow \gamma + q$. This dominance is preserved at higher orders, indicating that the experimental inclusive cross section differential in p_T may be used to determine the density of gluons in the initial hadrons.²⁾

In this paper, we summarize recent work^{3), 4)}, in which we demonstrate that the Compton subprocess, $q + g \rightarrow \gamma^* + q$ also dominates the Drell-Yan cross section in polarized and unpolarized proton-proton reactions for values of the transverse momentum Q_T of the pair that are larger than roughly half of the pair mass Q , $Q_T > Q/2$. The Drell-Yan process is therefore a valuable, heretofore overlooked, independent source of constraints on the spin-averaged and spin-dependent *gluon densities*. Although the Drell-Yan cross section is smaller than the prompt photon cross section, massive lepton pair production is cleaner theoretically since long-range fragmentation contributions are absent as are the experimental and theoretical complications associated with isolation of the real photon.⁵⁾ Moreover, the dynamics of spin-dependence in hard-scattering processes is a sufficiently complex topic, and its understanding at an early stage in its development, that several defensible approaches for extracting polarized parton densities deserve to be pursued with the expectation that

consistent results must emerge.

§2. Unpolarized Cross Sections

In this Section differential cross sections for massive lepton-pair production are presented as functions of Q_T at collider energies. We work in the $\overline{\text{MS}}$ renormalization scheme and set the renormalization and factorization scales equal. We employ the MRST98-1 set of spin-averaged parton densities⁶⁾ and a two-loop expression for the strong coupling strength $\alpha_s(\mu)$, with five flavors and appropriate threshold behavior at $\mu = m_b$. We use the value $\Lambda^{(4)} = 300$ MeV of the MRST98-1 set. The strong coupling strength α_s is evaluated at a hard scale $\mu = \sqrt{Q^2 + Q_T^2}$. We offer results for three values of RHIC center-of-mass energy, $\sqrt{S} = 50$, 200, and 500 GeV.

For $\sqrt{S} = 200$ GeV, we present the invariant inclusive cross section $Ed^3\sigma/dp^3$ as a function of Q_T in Fig. 1. Shown are the $q\bar{q}$ and qg perturbative contributions to the cross section at leading order and at next-to-leading order. For $Q_T < 1.5$ GeV, the $q\bar{q}$ contribution exceeds that of qg channel. However, for values of $Q_T > 1.5$ GeV, the qg contribution becomes increasingly important. The qg contribution accounts for about 80 % of the rate once $Q_T \simeq Q$. Subprocesses other than those initiated by the $q\bar{q}$ and qg initial channels contribute negligibly.

In Ref. 4), results are shown also for a larger value of Q : $11 < Q < 12$ GeV, and for the interval $2.0 < Q < 3.0$ GeV. The fractions of the cross sections attributable to qg initiated subprocesses again increase with Q_T , growing to 80 % for $Q_T \simeq Q$. In region $2.0 < Q < 3.0$ GeV, one would doubt the reliability of leading-twist perturbative descriptions of the cross section $d\sigma/dQ$, *integrated* over all Q_T . However, for values of Q_T that are large enough, $\alpha_s(Q_T)$ is small and a perturbative description of the Q_T dependence of $d^2\sigma/dQdQ_T$ ought

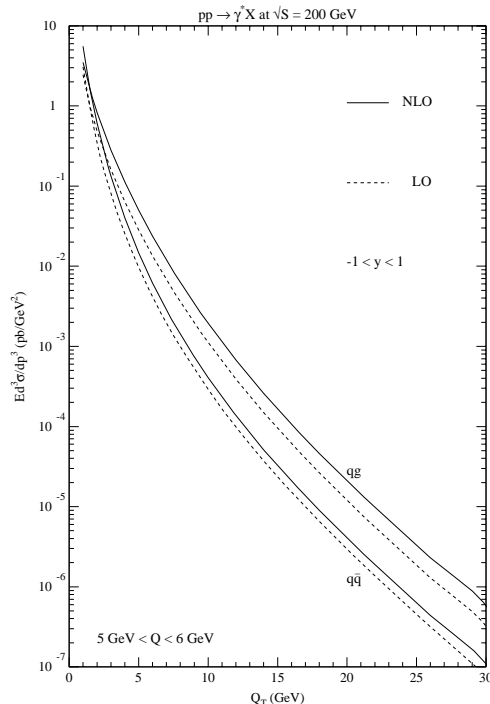


Fig. 1. Lowest order and next-to-leading order perturbative calculations of $Ed^3\sigma/dp^3$ as a function of Q_T for $pp \rightarrow \gamma^* X$ at $\sqrt{S} = 200$ GeV. Contributions from the qg and $q\bar{q}$ channels are shown separately. The results are averaged over the rapidity interval $-1.0 < y < 1.0$ and over the interval $5.0 < Q < 6.0$ GeV.

to be justified.

In Fig. 2, we provide next-to-leading order predictions of the differential cross section as a function of Q_T for three values of the center-of-mass energy. In order to ascertain the range of values of Q_T that can be explored, we take $Ed^3\sigma/dp^3 = 10^{-3}\text{pb/GeV}^2$ as the minimum accessible cross section. This level is based on assumed luminosities⁷⁾ of $8 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1}$ at $\sqrt{S} = 200$ GeV, and $2 \times 10^{32}\text{cm}^{-2}\text{sec}^{-1}$ at $\sqrt{S} = 500$ GeV, along with runs of 10 weeks per year, equivalent to integrated luminosities of $320\text{pb}^{-1}\text{year}^{-1}$ and $800\text{pb}^{-1}\text{year}^{-1}$. Better performance than anticipated of the accelerator and extended running time will increase the reach. The luminosity scales roughly with \sqrt{S} because the focusing power can be increased as the energy is reduced. This capability saturates near 70 GeV/c per beam, and below about $\sqrt{S} = 140$ GeV the luminosity drops roughly as S .

Adopting the nominal value $Ed^3\sigma/dp^3 = 10^{-3}\text{pb/GeV}^2$, we use the curves in Fig. 2 to establish that the massive lepton-pair cross section may be measured to $Q_T = 7.5, 14$, and 18.5 GeV at $\sqrt{S} = 50, 200$, and 500 GeV, respectively, when $2 < Q < 3$ GeV, and to $Q_T = 6, 11.5$, and 15 GeV when $5 < Q < 6$ GeV. In terms of reach in the fractional momentum x_{gluon} carried by the gluon, these values of Q_T may be converted to $x_{gluon} \simeq x_T = 2Q_T/\sqrt{S} = 0.3, 0.14$, and 0.075 at $\sqrt{S} = 50, 200$, and 500 GeV when $2 < Q < 3$ GeV, and to $x_{gluon} \simeq 0.24, 0.115$, and 0.06 when $5 < Q < 6$ GeV. On the face of it, the smallest value of \sqrt{S} provides the greatest reach in x_{gluon} . However, the reliability of fixed-order perturbative QCD as well as dominance of the qg subprocess improve with greater Q_T . The maximum value $Q_T \simeq 7.5$ GeV attainable at $\sqrt{S} = 50$ GeV argues for a larger \sqrt{S} .

Comparing the magnitudes of the prompt photon and massive lepton pair production cross sections⁴⁾, we note that the inclusive prompt photon cross section is a factor of 1000 to 4000 greater than the massive lepton-pair cross section integrated over the mass interval $2.0 < Q < 3.0$ GeV, depending on the value of Q_T . This factor is attributable in large measure to the factor $\alpha_{em}/(3\pi Q^2)$ associated with the decay of the virtual photon to $\mu^+\mu^-$. Again

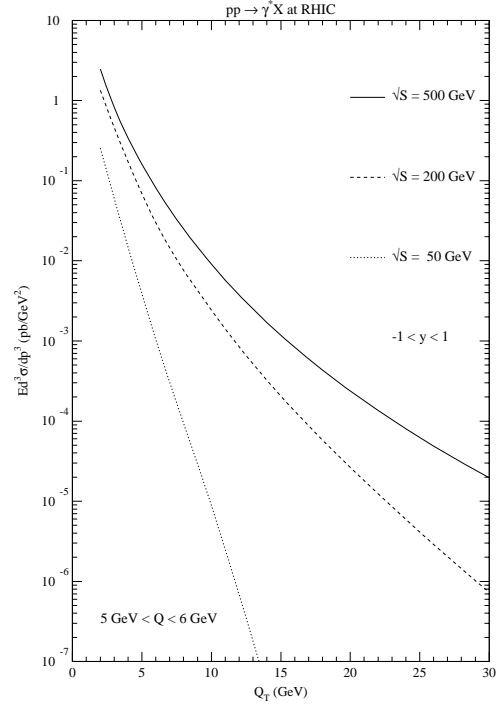


Fig. 2. Differential cross sections $Ed^3\sigma/dp^3$ as a function of Q_T for for $pp \rightarrow \gamma^* + X$ at $\sqrt{S} = 50, 200$, and 500 GeV, averaged over the rapidity interval $-1.0 < y < 1.0$ and the mass interval $5.0 < Q < 6.0$ GeV.

taking $Ed^3\sigma/dp^3 = 10^{-3}\text{pb/GeV}^2$ as the minimum accessible cross section, we establish that the real photon cross section may be measured to $p_T = 14, 33, \text{ and } 52 \text{ GeV}$ at $\sqrt{S} = 50, 200, \text{ and } 500 \text{ GeV}$, respectively. The corresponding reach in x_T is $x_T = 2p_T/\sqrt{S} = 0.56, 0.33, \text{ and } 0.21$ at $\sqrt{S} = 50, 200, \text{ and } 500 \text{ GeV}$.

The significantly smaller cross section in the case of massive lepton-pair production means that the reach in x_{gluon} is restricted to a factor of about two to three less, depending on \sqrt{S} and Q , than that potentially accessible with prompt photons in the same sample of data. Nevertheless, it is valuable to be able to investigate the gluon density with a process that has reduced experimental and theoretical systematic uncertainties from those of the prompt photon case.

In Ref. 3) we compared our spin-averaged cross sections with available fixed-target and collider data on massive lepton-pair production at large values of Q_T , and we were able to establish that fixed-order perturbative calculations, without resummation, should be reliable for $Q_T > Q/2$. The region of small Q_T and the matching region of intermediate Q_T are complicated by some level of phenomenological ambiguity. Within the resummation approach, phenomenological non-perturbative functions play a key role in fixing the shape of the Q_T spectrum at very small Q_T , and matching methods in the intermediate region are hardly unique. For the goals we have in mind, it would appear best to restrict attention to the region $Q_T \geq Q/2$.

§3. Predictions for Spin Dependence

Given theoretical expressions that relate the spin-dependent cross section at the hadron level to spin-dependent partonic hard-scattering matrix elements and polarized parton densities, we must adopt models for spin-dependent parton densities in order to obtain illustrative numerical expectations. The current deep inelastic scattering data do not constrain the polarized gluon density tightly, and most groups present more than one plausible parametrization. Gehrmann and Stirling (GS)⁸⁾ present three such parametrizations, labelled GSA, GSB, and GSC. In the GSA and GSB sets, $\Delta G(x, \mu_o)$ is positive for all x , whereas in the GSC set $\Delta G(x, \mu_o)$ changes sign. After evolution to $\mu_f^2 = 100 \text{ GeV}^2$, $\Delta G(x, \mu_f)$ remains positive for essentially all x in all three sets, but its magnitude is small in the GSB and GSC sets. We use the three parametrizations suggested by Gehrmann and Stirling, and we verified that the positivity requirement $|\Delta f_h^j(x, \mu_f)/f_h^j(x, \mu_f)| \leq 1$ is satisfied.

Other sets of spin-dependent parton densities have been published, e.g., the set of Glück, Reya, Stratmann, and Vogelsang (GRSV).⁹⁾ The three GS parametrizations of the polarized gluon density span a range of possibilities that is very similar to that spanned by the four

gluon densities of GRSV. It is not our purpose to "test", or to suggest tests, of existing parametrizations all of which will have been modified substantially by the time data are available from RHIC. Rather, we use the existing parametrizations as illustrative possibilities in order to estimate the range of magnitudes that might be expected for A_{LL} at RHIC energies and to gauge the sensitivity that measurements of spin dependence in massive lepton-pair production may offer. The goal, after all, is to measure the polarized gluon density, not to test parametrizations.

In this Section, we present two-spin longitudinal asymmetries for massive lepton-pair production as a function of transverse momentum. Results are displayed for pp collisions at the center-of-mass energies $\sqrt{S} = 50, 200$, and 500 GeV typical of the Brookhaven RHIC collider.

The two-spin longitudinal asymmetries, A_{LL} , are computed in leading-order. More specifically, we use leading-order spin-averaged and spin-dependent partonic subprocess cross sections, $\hat{\sigma}$ and $\Delta\hat{\sigma}$, with next-to-leading order spin-averaged and spin-dependent parton densities and a two-loop expression for α_s . The choice of a leading-order expression for $\Delta\hat{\sigma}$ is required because the full next-to-leading order derivation of $\Delta\hat{\sigma}$ has not been completed for massive lepton-pair production. Experience with prompt photon production indicates that the leading-order and next-to-leading order results for the asymmetry are similar so long as both are dominated by the qg subprocess. To obtain the spin-dependent cross section, we use the GS polarized parton densities with the GS value $\Lambda^{(4)} = 231$ MeV. This value of $\Lambda^{(4)}$ differs from the MRST value $\Lambda^{(4)} = 300$ MeV for the unpolarized densities used in our computation of the spin-averaged cross section. The use of different values of $\Lambda^{(4)}$ for the spin-dependent and spin-averaged cross sections may appear unfortunate. However, there is not much of an alternative at present short of creating new sets of polarized parton densities based on the most up-to-date spin-averaged densities that we prefer to use for the spin-averaged cross section. To change $\Lambda^{(4)}$

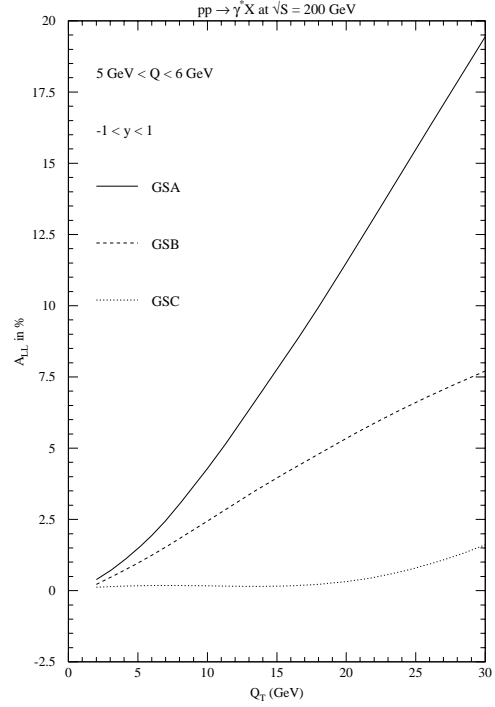


Fig. 3. Computed longitudinal asymmetry A_{LL} as a function of Q_T for $pp \rightarrow \gamma^* X$ at $\sqrt{S} = 200$ GeV. The asymmetry is averaged over the rapidity interval $-1.0 < y < 1.0$ and mass interval $5.0 < Q < 6.0$ GeV, for three choices of the polarized parton densities, GSA, GSB, and GSC.

arbitrarily in the GS set to equal that of the MRST set would distort the spin-dependent densities.

In Fig. 3, we present the two-spin longitudinal asymmetries, A_{LL} , as a function of Q_T for the three GS choices of the polarized gluon density. The asymmetry becomes sizable for large enough Q_T for the GSA and GSB parton sets but not in the GSC case. The asymmetry A_{LL} is nearly independent of the pair mass Q as long as Q_T is not too small. This feature should be helpful for the accumulation of statistics; small bin-widths in mass are not necessary, but the J/ψ and Υ resonance regions should be excluded.

As noted above the qg subprocess dominates the *spin-averaged* cross section. It is interesting and important to inquire whether this dominance persists in the spin-dependent situation. In Fig. 4, we compare the contribution to the asymmetry from the polarized qg subprocess with the complete answer for all three sets of parton densities. The qg contribution is more positive than the full answer for values of Q_T that are not too small; the full answer is reduced by the negative contribution from the $q\bar{q}$ subprocess for which the parton-level asymmetry $\hat{a}_{LL} = -1$. At small Q_T , the net asymmetry may be driven negative by the $q\bar{q}$ contribution, and based on our experience with other calculations, from processes such as gg that contribute in next-to-leading order. For the GSA and GSB sets, we see that once it becomes sizable (e.g., 5% or more), the total asymmetry from all subprocesses is dominated by the large contribution from the qg subprocess.

As a general rule in studies of polarization phenomena, many subprocesses can contribute small and conflicting asymmetries. Asymmetries are readily interpretable only in situations where the basic dynamics is dominated by one major subprocess and the overall asymmetry is sufficiently large. In the case of massive lepton-pair production that is the topic of this paper, when the overall asymmetry A_{LL} itself is small, the contribution

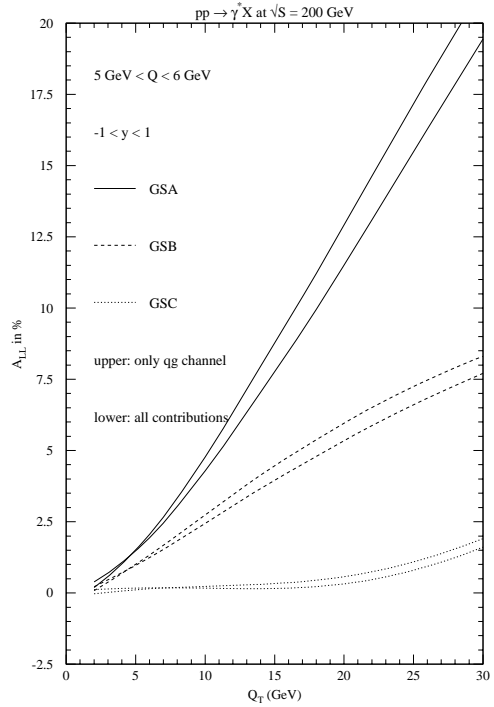


Fig. 4. Comparison of the contribution of the qg subprocess (upper curve) to the longitudinal asymmetry A_{LL} with the total (lower curve) as a function of Q_T for $pp \rightarrow \gamma^* X$ at $\sqrt{S} = 200$ GeV. The asymmetry is averaged over the rapidity interval $-1.0 < y < 1.0$ and over the interval $5.0 < Q < 6.0$ GeV. Results are shown for three sets of spin-dependent parton densities.

from the qg subprocess cannot be said to dominate the answer. However, if a large asymmetry is measured, similar to that expected in the GSA case at the larger values of Q_T , Fig. 4 shows that the answer is dominated by the qg contribution, and data will serve to constrain $\Delta G(x, \mu_f)$. If $\Delta G(x, \mu_f)$ is small and a small asymmetry is measured, such as for the GSC parton set, or at small Q_T for all parton sets, one will not be able to conclude which of the subprocesses is principally responsible, and no information could be adduced about $\Delta G(x, \mu_f)$, except that it is small.

In Fig. 5, we examine energy dependence. For Q_T not too small, A_{LL} in massive lepton pair production is well described by a scaling function of $x_T = 2Q_T/\sqrt{S}$, $A_{LL}(\sqrt{S}, Q_T) \simeq h_{\gamma^*}(x_T)$. In our discussion of the spin-averaged cross sections, we took $E d^3\sigma/dp^3 = 10^{-3}\text{pb}/\text{GeV}^2$ as the minimum accessible cross section. Longitudinal asymmetries $A_{LL} = 20\%$, 7.5% , and 3% are predicted at this level of cross section at $\sqrt{S} = 50$, 200 , and 500 GeV when $2 < Q < 3$ GeV, and $A_{LL} = 11\%$, 5% , and 2% when $5 < Q < 6$ GeV. For a given value of Q_T , smaller values of \sqrt{S} result in greater asymmetries because $\Delta G(x)/G(x)$ grows with x .

The predicted cross sections in Fig. 2 and the predicted asymmetries in Fig. 5 should make it possible to optimize the choice of center-of-mass energy at which measurements might be carried out. At $\sqrt{S} = 500$ GeV, asymmetries are not appreciable in the interval of Q_T in which event rates are appreciable. At the other extreme, the choice of $\sqrt{S} = 50$ GeV does not allow a sufficient range in Q_T . Accelerator physics considerations favor higher energies since the instantaneous luminosity increases with \sqrt{S} . Investigations in the energy interval $\sqrt{S} = 150$ to 200 GeV would seem preferred.

So long as $Q_T \geq Q$, the asymmetry in massive lepton-pair production is about the same size as that in prompt real photon production, as might be expected from the strong similarity of the production dynamics in the two cases.

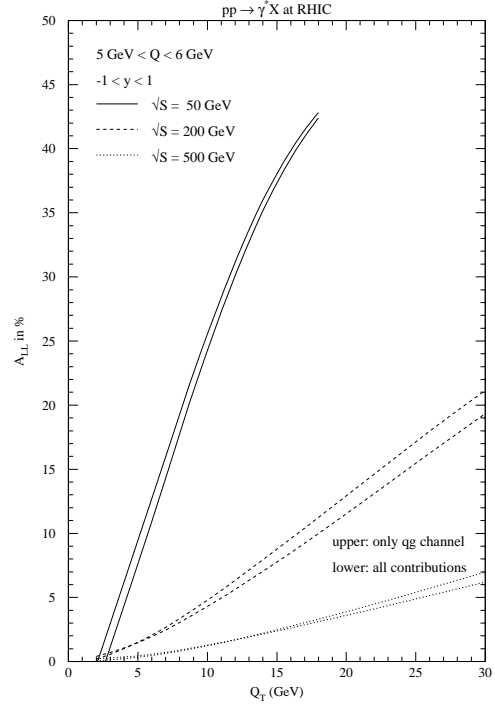


Fig. 5. Computed longitudinal asymmetry A_{LL} as a function of Q_T for for $pp \rightarrow \gamma^* + X$ at $\sqrt{S} = 50$, 200 , and 500 GeV, averaged over the rapidity interval $-1.0 < y < 1.0$ and the mass interval $5.0 < Q < 6.0$ GeV. Shown are both the complete answer at leading-order and the contribution from the qg subprocess. The GSA set of polarized parton densities is used.

As in massive lepton-pair production, A_{LL} in prompt photon production is well described by a scaling function of $x_T = 2p_T/\sqrt{S}$, $A_{LL}(\sqrt{S}, p_T) \simeq h_\gamma(x_T)$. For $Ed^3\sigma/dp^3 = 10^{-3}\text{pb/GeV}^2$, we predict longitudinal asymmetries $A_{LL} = 31\%$, 17% , and 10% in real prompt photon production at $\sqrt{S} = 50, 200$, and 500 GeV.

Although the qg Compton subprocess is dominant, one might question whether uncertainties associated with the quark density compromise the possibility to determine the gluon density. In this context, it is useful to recall¹⁰⁾ that when the Compton subprocess is dominant, the spin-averaged cross section may be rewritten in a form in which the quark densities do not appear explicitly:

$$\frac{Ed^3\sigma_{h_1h_2}^{l\bar{l}}}{dp^3} \approx \int dx_1 \int dx_2 \left(\frac{F_2(x_1, \mu_f^2)}{x_1} G(x_2, \mu_f^2) \frac{Ed^3\hat{\sigma}_{qg}^{l\bar{l}}}{dp^3} + (x_1 \leftrightarrow x_2) \right). \quad (3.1)$$

Likewise, the spin-dependent cross section may be expressed as¹⁰⁾

$$\frac{Ed^3\Delta\sigma_{h_1h_2}^{l\bar{l}}}{dp^3} \approx \int dx_1 \int dx_2 \left(2g_1(x_1, \mu_f^2) \Delta G(x_2, \mu_f^2) \frac{Ed^3\Delta\hat{\sigma}_{qg}^{l\bar{l}}}{dp^3} + (x_1 \leftrightarrow x_2) \right). \quad (3.2)$$

In Eqs. (3.1) and (3.2), $F_2(x, \mu_f^2)$ and $g_1(x, \mu_f^2)$ are the proton structure functions *measured* in spin-averaged and spin-dependent deep-inelastic lepton-proton scattering. It is evident that the production of massive lepton-pairs at large enough Q_T will determine the gluon density provided the proton structure functions are measured well in deep-inelastic lepton-proton scattering.

§4. Discussion and Conclusions

In this paper we summarize a calculation of the longitudinal spin-dependence of massive lepton-pair production at large values of transverse momentum. We provide polarization asymmetries as functions of transverse momenta that may be useful for estimating the feasibility of measurements of spin-dependent cross sections in future experiments at RHIC collider energies. The Compton subprocess dominates the dynamics in longitudinally polarized proton-proton reactions as long as the polarized gluon density $\Delta G(x, \mu_f)$ is not too small. As a result, two-spin measurements in massive lepton-pair production in polarized pp scattering should constrain the size, *sign*, and Bjorken x dependence of $\Delta G(x, \mu_f)$.

Significant values of A_{LL} (i.e., greater than 5 %) may be expected for $x_T = 2Q_T/\sqrt{S} > 0.10$ if the polarized gluon density $\Delta G(x, \mu_f)$ is as large as that in the GSA set of polarized parton densities. If so, the data could be used to determine the polarization of the gluon

density in the nucleon. On the other hand, for small $\Delta G(x, \mu_f)$, dominance of the qg subprocess is lost, and $\Delta G(x, \mu_f)$ is inaccessible.

Various methods have been discussed in the literature to access the spin-averaged and spin-dependent gluon densities. These include inclusive/isolated prompt photon production at large transverse momentum (with or without a tagged recoil jet); the Drell-Yan process at large Q_T , as advocated in this paper; hadronic jet production at large p_T ; and heavy flavor production such as charm (c) and bottom (b), thought to be mediated by the subprocess $g + g \rightarrow c + \bar{c} + X$. Each has its possibilities and drawbacks. Hadronic jet production benefits from the largest rate, but the large number of contributing subprocesses and the complications of jet definition mitigate against it. Inclusive prompt photon production is theoretically clean but for the non-perturbative long-range fragmentation contribution. However, experimenters measure *isolated* photons, and isolation renders the contact with theory somewhat murky.⁵⁾ The Drell-Yan process seems ideal, but its rate is relatively low. Heavy flavor production is an enigma. The charm quark is so light that calculations based on fixed-order perturbative QCD are of questionable reliability at collider energies. The bottom quark seems to be heavy enough to justify perturbation theory, but why does the experimental cross section at Fermilab collider energies exceed next-to-leading order QCD predictions by a factor of 2 or 3?

The dynamics of spin-dependence in hard-scattering processes is a sufficiently complex topic, and its understanding at an early stage in its development, that several defensible approaches for extracting polarized parton densities deserve to be pursued with the expectation that consistent results must emerge. For the first time, RHIC offers an opportunity to explore the dynamics of spin dependence in hadron reactions at values of the hard scale that are sufficiently large that perturbative QCD ought to work. It will take several years of experimentation and analysis for a clear and consistent picture to emerge of spin-dependent parton densities, just as it has in the study of spin-averaged parton densities. The long term support of this program by the Brookhaven Laboratory and by the funding agencies will be essential for realization of the considerable potential that RHIC offers.

Acknowledgments

ELB is pleased to acknowledge the warm hospitality of the RIKEN Laboratory and of the Symposium hosts, particularly Shunzo Kumano, Masayasu Ishihara, Shunichi Kobayashi, Toshi-Aki Shibata, and Koichi Yazaki. Work in the High Energy Physics Division at Argonne National Laboratory is supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38. This work was supported in part by

DOE contract DE-AC05-84ER40150 under which Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility. MK is supported by Bundesministerium für Bildung und Forschung under Contract 05 HT9GUA 3, by Deutsche Forschungsgemeinschaft under Contract KL 1266/1-1, and by the European Commission under Contract ERBFMRXCT980194.

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